CONTROL OF LASER RADIATION PARAMETERS

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Mode locking in a bismuth fibre laser by using a SESAM

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***Abstract*. By using a semiconductor saturable-absorber mirror (SESAM) optimised for operation in the spectral range from 1100 to 1200 nm, passive mode locking is obtained in a cw bismuth-doped fibre laser. Pumping was performed by a cw ytterbium-doped fibre laser at a wavelength of 1075 nm. The operation of the laser is studied by using either a fibre Bragg grating or a loop fibre Sagnac mirror as the output resonator mirror. Stable laser pulses of duration from 50 ps to 3.5 ns, depending on the output mirror type, were generated. The pulse repetition rate was 11 MHz at a wavelength of ~1160 nm and the maximum spectral width of 2.1 nm. The maximum average output power was 7.8 mW upon pumping by 1140 mW.**

Keywords: *bismuth fibre laser, mode locking, SESAM.*

1. Introduction

Fibre lasers offer a number of significant advantages such as their compactness, high efficiency, reliability and simplicity in operation. Studies are now underway on the improvement of the output parameters of fibre lasers, in particular, on the extension of their emission range and shortening laser pulses. A new type of the active optical fibre with a core doped with bismuth atoms was recently investigated [1]. The luminescence spectrum of bismuth compounds in the fibre lies in the region from 1.1 to 1.3 μm, which gives promise that ultrashort subpicosecond pulses may be generated in the mode-locking regime.

At present cw oscillation was obtained in a bismuth-doped fibre laser pumped by an ytterbium-doped fibre laser [2 – 5]. The output power was 460 and 550 mW at the maximum efficiency 29 % [2] and 24 % [3] at wavelengths of 1146 and 1200 nm, respectively. The maximum output power of 15 W was obtained at a wavelength of 1160 nm [5].

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In [6], we have demonstrated for the first time cw operation of a bismuth laser in the passive mode-locking regime, which was initiated and maintained by using a semiconductor saturable-absorber mirror (SESAM) [7, 8]. The laser emitted ~50-ps pulses with the maximum average power of 2 mW. In this paper, we studied in more detail the passive mode-locking regime in a bismuth-doped few-mode fibre laser by using either a fibre Bragg grating (FBG) or a broadband loop fibre Sagnac mirror as the output mirror of the resonator.

2. Bismuth-doped optical fibre

We used a silica fibre with a core doped with bismuth. A preform for fibre drawing was fabricated by the MCVD method. The atomic concentration of bismuth did not exceed 0.02 % (the minimum measurable value). Such a low concentration was used because the lasing efficiency considerably decreased with increasing the bismuth concentration [1 – 2]. Due to the low bismuth concentration, both the absorption coefficient at the pump wavelength (0.9 dB m^{-1} at 1075 nm) and the gain for radiation propagating in the fibre (~0.5 dB m^{-1} at 1160 nm for complete saturation) were rather small. For this reason, to provide the efficient absorption of the pump radiation and to achieve average cw radiation powers at a level of several watts [2 – 4] and tens of watts [5], it is necessary to use bismuth-doped fibres of length ~100 m. Mode locking

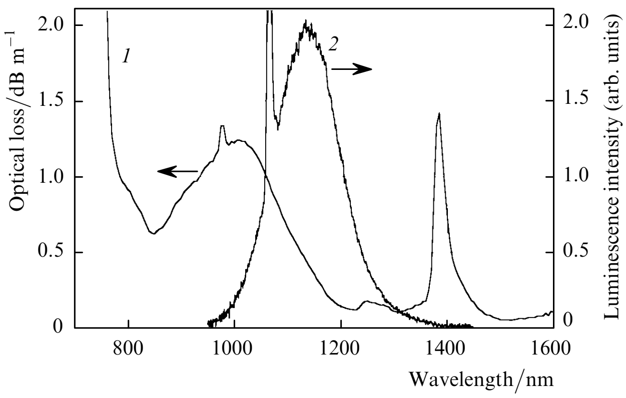

Figure 1. Optical loss (*1*) and luminescence (*2*) spectra of an optical fibre doped with bismuth atoms [the fibre core composition: $97.70SiO_2 - 2.25Al_2O_3 - (< 0.02)Bi_2O_3$]; the bands at 800 and 1000 nm belong to bismuth compounds, while the bands at 945, 1245, and 1385 nm belong to OH groups.

cannot be practically achieved in such long fibres due to a great group velocity dispersion (GVD). Because of this, we studied an active bismuth-doped fibre of length 4.8 m. Figure 1 presents the optical loss and luminescence spectra of this fibre. The parameters of the active bismuth-doped fibre measured in our experiments are presented below.

Concentration of bismuth atoms (%)	< 0.02
Diameter of the fundamental-mode field (at the e^{-2} intensity level) at 1160 nm/μm	10.9 ± 0.1
Fibre length/m	4.8
Upper laser level lifetime/ms	~ 1
Pump radiation loss at 1075 nm/dB	4.3
Second-order dispersion β_2 at 1160 nm/ps^2 m^{-1}	1.1×10^{-2}

3. Experimental setup

Experimental schemes of a bismuth-doped fibre laser are presented in Fig. 2. All the passive fibre elements of the laser resonator were fabricated of a single-mode Flexcore fibre with the fundamental mode diameter 7.3 ± 0.1 μm and the second-order dispersion $\beta_2 \approx 1.5 \times 10^{-2}$ ps^2 m^{-1} at 1160 nm. The bismuth-to-passive fibre coupling loss was reduced to 0.4 dB by choosing properly the parameters of the arc discharge of a Corning A60 fibre coupler.

As the output mirror in the scheme in Fig. 2a, FBGs with the high reflectance and different widths of the reflection spectrum were used. The highly reflecting output mirror should be used because of the low gain of laser radiation in the bismuth fibre.

The output mirror in the scheme in Fig. 2b was a loop broadband fibre Sagnac mirror with the reflectance of 82 % or 95 % at 1160 nm. These mirrors exclude the spectral selection of radiation, which is inherent in FBGs, thereby providing a broader laser emission spectrum. The second mirror of the laser resonator in both schemes was a SESAM to which the fibre end-face cleaved at a right angle was brought into contact. The SESAM based on the GaInNAs structure was grown by the method of molecular-beam epitaxy on a GaAs substrate and optimised for operation in the spectral range from 1100 to 1200 nm [7, 8]. The SESAM operated in the nearly resonance regime with a high contrast of the saturable radiation loss in it because the self-triggering of mode locking in a laser with a large positive GVD of the resonator can occur only in this case [7, 8].

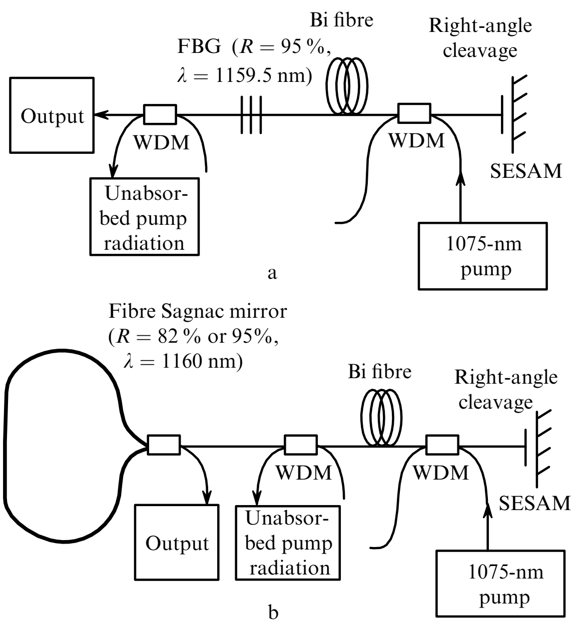

Figure 2. Experimental schemes of a pulsed bismuth laser with a FBG (a) and a fibre Sagnac mirror (b).

Pumping was performed by a 1.14-W, 1075-nm cw ytterbium-doped fibre laser through a wavelength-division multiplexer (WDM) with the efficient combining radiation at wavelengths 1075 and 1160 nm. The pump laser was based on an ytterbium-doped fibre of length 7 m with two FBGs used as resonator mirrors with reflectances ~ 100 % and 5 % at 1075 nm. The width of the pump line was ~ 0.05 nm. The ytterbium-doped fibre was pumped by a 975-nm laser diode with a multimode fibre pigtail. All the passive fibre components of the pump ytterbium laser were also fabricated of a single-mode Flexcore fibre with the fundamental mode of diameter 7.0 ± 0.1 μm at a wavelength of 1075 nm.

The output collimated radiation of the pulsed bismuth laser (the Gaussian beam diameter was ~ 500 μm) propagated through a spectral filter rejecting the residual pump radiation and was directed into the measurement unit of the experimental setup. The temporal parameters of laser pulses were measured with a 5-GHz Tektronix 7104 analogue oscilloscope, a germanium photodetector with a time response of 700 ps, and an Inrad5-14LDA autocorrelator operating in the noncollinear phase-matching regime in a lithium niobate crystal. Spectral measurements were performed by using an ANDO AQ6317B spectrum analyser with a spectral resolution of 0.01 nm. The average radiation power was measured with a Coherent FieldMaxII power meter with a semiconductor sensor.

4. Experimental results

4.1 Laser with a FBG

Initially [6], a FBG with the reflectance 75 % at 1161.6 nm and the reflection spectrum of width ~ 0.02 nm was used as the output mirror. Continuous lasing was obtained for the first time in the passive mode-locking regime with the pulse duration of ~ 50 ps at 1161.6 nm. We have managed to obtain a stable continuous mode locking and to exclude Q switching in the entire power range of the pump ytterbium laser up to the maximum value.

Because the minimum pulse duration is determined by the width of the spectrum, we attempted to use a FBG with a broader reflection spectrum. We employed a grating with the reflectance 95 % at 1159.5 nm and the width of the reflection spectrum 0.5 nm. Figure 3 shows a train of stable pulses generated by the laser with the FBG in the mode-locking regime. The laser linewidth was 0.2 nm, i.e. an order of magnitude larger than that in [6]. However, despite their large spectral width, laser pulses proved to be rather long (~ 3.5 ns in Fig. 4) and had some internal structure in the form of the amplitude modulation, which is confirmed by the measurement of the correlation function of the pulse intensity (Fig. 5), where the central peak (of width ~ 10 ps) corresponds to the presence of this internal unstable structure. Such an increase in the pulse duration and the appearance of the internal structure of the pulse can be explained by the fact that in the case of propagation of laser pulses with a broader spectrum, the GVD in a long fibre resonator and in a FBG plays a more important role in the

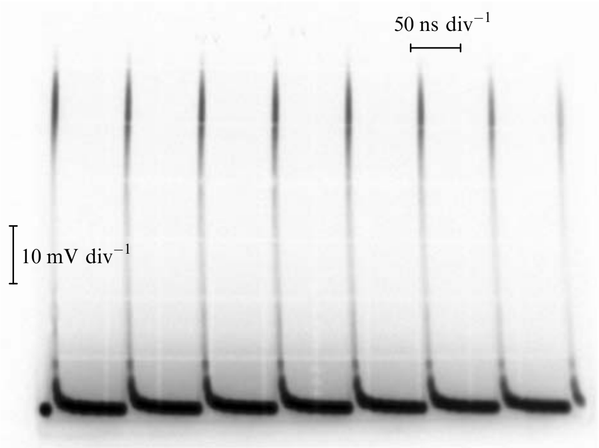

Figure 3. Pulse train generated by a bismuth laser with a FBG (laser scheme in Fig. 2a).

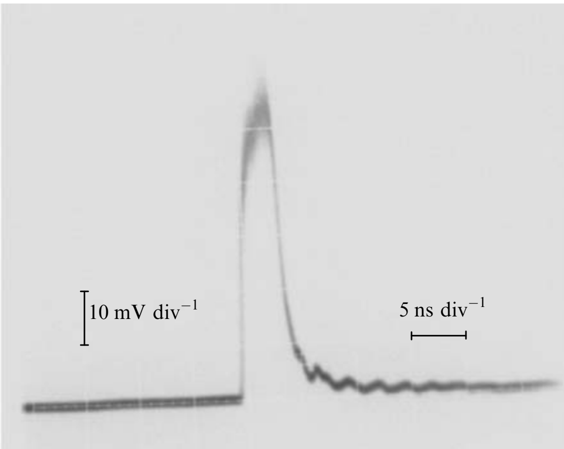

Figure 4. Oscillogram of a pulse generated by a bismuth laser with a FBG (laser scheme in Fig. 2a).

pulse formation. We can assume that nonlinear effects (self-phase modulation and four-wave mixing) also can become more significant. Thus, the increase in the spectral width obtained by using the FBG with a broader reflection

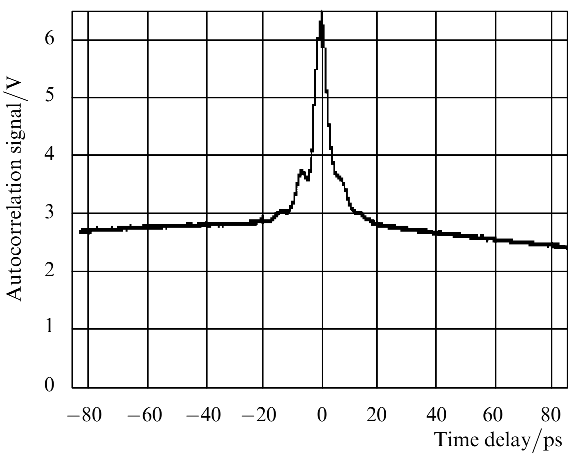

Figure 5. Autocorrelation intensity function of a bismuth laser with a FBG (laser scheme in Fig. 2a).

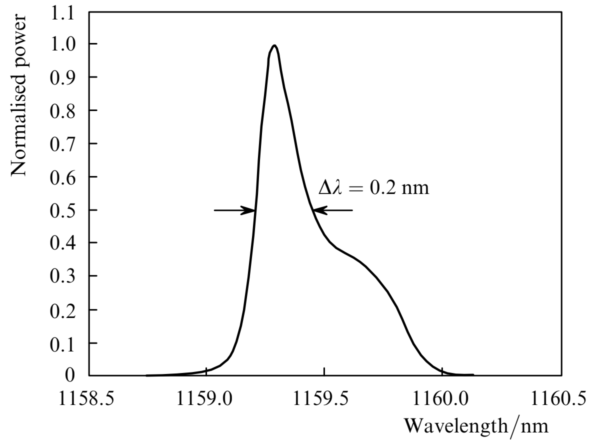

Figure 6. Emission spectrum of a bismuth laser with a FBG (laser scheme in Fig. 2a).

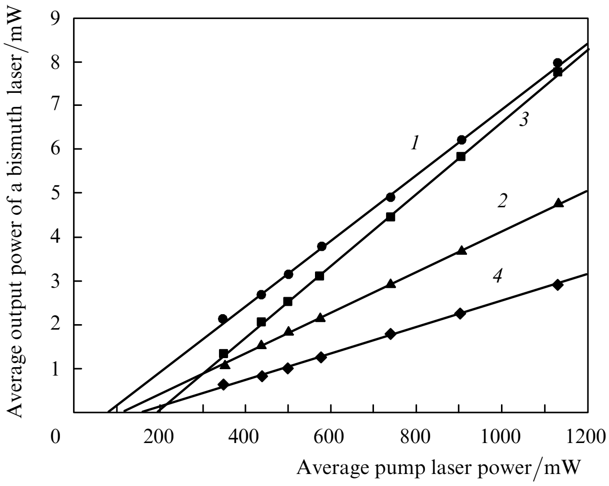

Figure 7. Slope efficiency of pulsed bismuth fibre lasers with a FBG (Fig. 2a) (the efficiency is 0.75 %) (*1*), with a FBG and an intracavity WDM (0.46 %) (*2*), with a Sagnac mirror (Fig. 2b), $R = 82$ % (the efficiency is 0.82 %) (3), with a Sagnac mirror (Fig. 2b), $R = 95$ % (the efficiency is 0.30 %) (*4*).

spectrum resulted not in a decrease in the pulse duration but, on the contrary, in its considerable increase.

Note that the temporal parameters of laser radiation do not change with increasing its average power. The shape of the laser emission spectrum (Fig. 6) also does not change with increasing the average output power. However, it does not exactly repeat the spectral profile of the FBG. It is obvious that laser pulses are not transform-limited and have the internal structure, possibly, in the form of the amplitude – phase modulation.

The maximum slope efficiency of the laser was 0.8 % [straight line (*1*) in Fig. 7]. Despite its comparatively low efficiency, the laser has a rather low threshold. Straight lines (*1*) and (*2*) in Fig. 7 differ in that in the case corresponding to straight line (*2*), the WDM in Fig. 2a, which couples the unabsorbed pump radiation out of the resonator, was placed inside the resonator, which enhanced the intracavity loss.

4.2 Laser with a fibre Sagnac mirror

To obtain even broader laser emission spectrum and to exclude the additional undesirable GVD of the FBG, we studied a laser (Fig. 2b) in which broadband loop fibre Sagnac mirrors were used as the output mirror. They excluded the spectral selection of radiation, which is inherent in FBGs, had the GVD inherent in a passive optical fibre from which the laser resonator was made and, therefore, only slightly increased the intracavity GVD.

By using the output Sagnac mirror with $R = 82\,\%$ in the scheme in Fig. 2b, we obtained stable continuous mode locking and excluded Q switching in the entire range of pump powers up to the maximum value (Fig. 8). Unlike the results obtained in the scheme with the FBG, smooth pulses of duration shorter than the response time of the photodetector (700 ps) were obtained (Fig. 9). The full width at half-maximum of the autocorrelation function of the pulse intensity was $\tau_a \approx 240$ ps (Fig. 10). The approximation of the autocorrelation function by a Gaussian gives the laser pulse duration $\tau_p \approx 170$ ps, which is independent of the output laser power. The laser linewidth measured in experiments exceeded 1 nm.

Thus, laser pulses proved to be considerably shorter than pulses generated by using a broadband FBG. This confirms the assumption that the GVD of the FBG considerably affects the formation of pulses. However, these pulses proved to be somewhat longer than pulses generated in a laser with a narrowband FBG, which can be explained by a

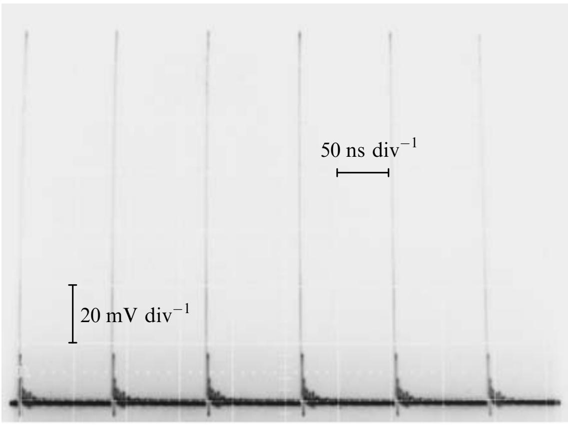

Figure 8. Pulse train generated by a bismuth laser with a fibre Sagnac mirror ($R = 82\,\%$).

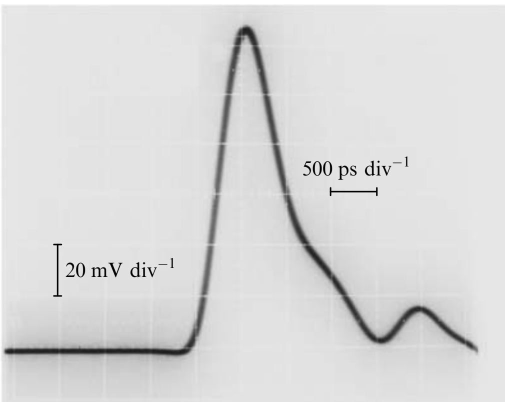

Figure 9. Oscillogram of a pulse generated by a bismuth laser with a fibre Sagnac mirror ($R = 82\,\%$).

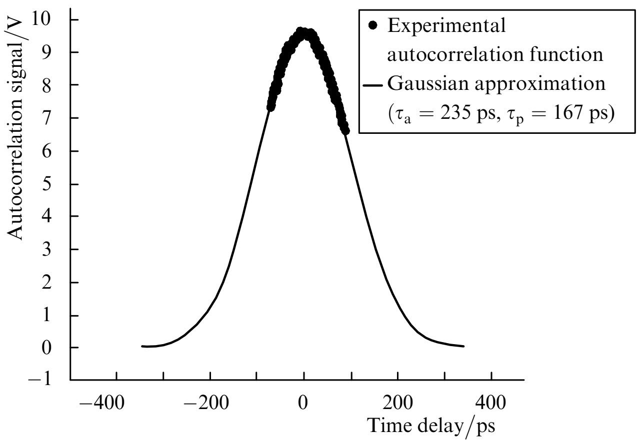

Figure 10. Autocorrelation intensity function of a bismuth laser with a fibre Sagnac mirror (laser scheme in Fig. 2b).

stronger influence of the positive GVD in a long fibre resonator in the case of propagation of broadband radiation.

The maximum of the laser emission spectrum was located in the region of 1160 nm (Fig. 11). The position of the spectrum, its width and shape depended on the output power of the laser. The red shift of the laser emission spectrum is caused by the passage of the SESAM to the nonresonance saturation operation regime with increasing the laser pulse energy [7, 8]. In this case, the emission spectrum considerably depends on several factors such as the positive GVD in the fibre resonator, the self-phase modulation, and nonlinear effects in the SESAM itself during the reflection of laser pulses from it [7, 8]. The maximum width of the laser spectrum was $\sim$2.1 nm for the maximum average output power 7.8 mW. The slope efficiency of the laser was 0.9 % [straight line (*3*) in Fig. 7].

When the reflectance of the Sagnac mirror was 95 %, the temporal and spectral parameters of laser radiation depended considerably on the output power. For moderate output powers lower than 0.83 mW, lasing was observed in the combined Q-switching and mode-locking regime; how-

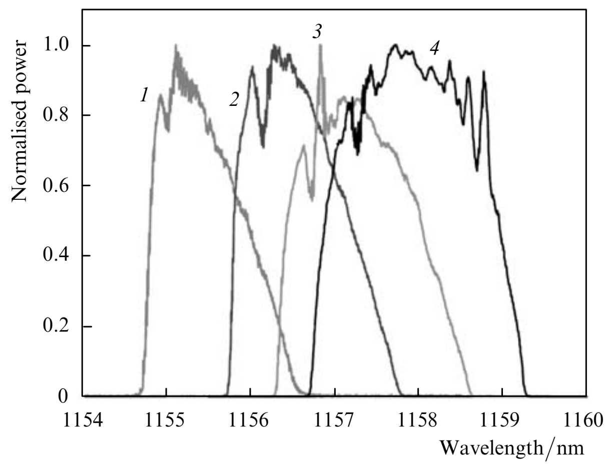

Figure 11. Dependences of the position and shape of the emission spectrum of a bismuth laser with a fibre Sagnac mirror ($R = 82\,\%$) on the average output power: $P_{out} = 1.36$ mW, $\Delta\lambda = 1.16$ nm (*1*); $P_{out} = 2.48$ mW, $\Delta\lambda = 1.38$ nm (*2*); $P_{out} = 4.48$ mW, $\Delta\lambda = 1.59$ nm (*3*); $P_{out} = 7.77$ mW, $\Delta\lambda = 2.07$ nm (*4*).

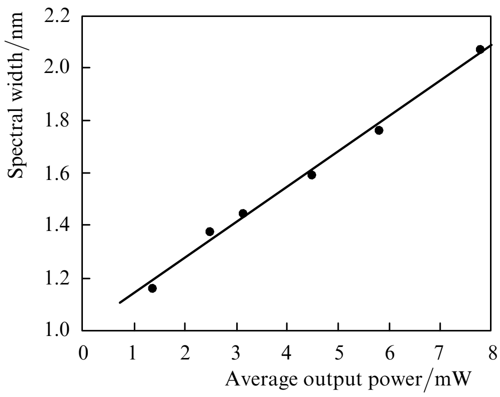

Figure 12. Dependence of the width of the emission spectrum of a bismuth laser with a fibre Sagnac mirror ($R = 82\,\%$) on the average output power.

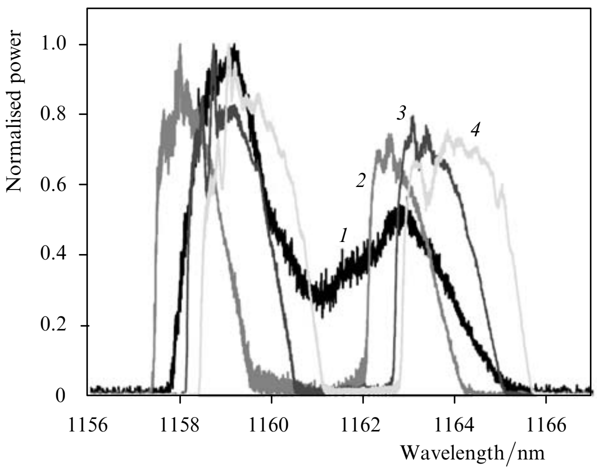

Figure 14. Dependences of the position and shape of the emission spectrum of a bismuth laser with a fibre Sagnac mirror ($R = 95\,\%$) on the average output power: $P_{\mathrm{out}} = 0.63$ (*1*), 1.01 (*2*), 1.74 (*3*), and 2.93 mW (*4*).

ever, pulses were unstable in time (Fig. 13a). When the average radiation power exceeded 0.83 mW, mode-locked pulses were stabilised; however, 'beats' appeared with a period of $\sim$4 ms in the output signal (Fig. 13b). The passage to the stable mode-locking regime was accompanied by a drastic change in the shape of the laser spectrum (Fig. 14): one spectral band split into two bands of almost the same width separated by 4.5 nm.

As the average radiation power further increased, these spectral bands broadened and shifted as a whole to the red.

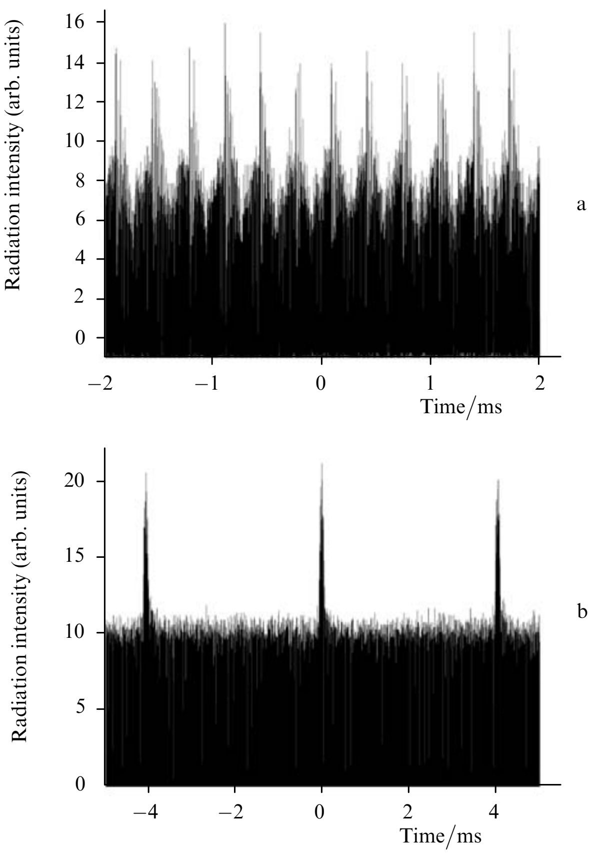

Figure 13. Oscillograms of the emission of a bismuth laser with a fibre Sagnac mirror ($R = 95\,\%$): combined regime of unstable mode-locking pulses and Q switching (a) and the regime of stable mode-locking pulses and 'beats' with a period of 4 ms, which are produced upon the overlap of two pulses corresponding to different spectral bands.

Because each of the spectral bands corresponds to its own pulse repetition period, the overlap of two systems of pulses corresponding to these bands leads to the appearance of 'beats' in the output laser signal at the difference pulse repetition rate. Upon the overlap of two pulses from different spectral bands, they are added incoherently and the radiation intensity doubles, as shown in Fig. 13b. Because adjacent pulses are also partially overlapped in this case, their incoherent summation leads to the increase in the radiation intensity, but to a lesser degree.

The splitting of the laser spectrum into two bands can be caused both by a stronger saturation of the SESAM due to the increase in the pulse energy in a higher-Q resonator [7, 8] and by the influence of the large positive GVD. The slope efficiency of the laser was 0.3 % at the maximum average power of 4 mW [straight line (*4*) in Fig. 7].

The resonator with a broad spectral minimum of losses, which was provided by a broadband fibre Sagnac mirror, favoured lasing in the mode-locking regime with a rather broad spectrum. However, the large GVD prevented the generation of short laser pulses in the resonator with a broad spectrum corresponding to these pulses.

To compensate the GVD in the resonator, we attempted to use a microstructure fibre. Such a fibre with the dispersion $D \approx 70$ ps nm^{-1} km^{-1} and length 3 m was introduced into the resonator with the help of Flexcore fibre pieces. However, because of a considerably mismatch between the diameters of mode spots of the fibres (2.6 μm for the microstructure fibre at 1160 nm), the coupling loss amounting to 10 dB quenched lasing.

5. Conclusions

We have studied a bismuth-doped fibre laser operating in the passive mode-locking regime initiated and maintained by a SESAM. Stable pulses of duration from 50 ps to 3.5 ns were generated in the continuous passive mode-locking regime. The width of the emission spectrum was broadened by using FBGs or broadband loop fibre Sagnac mirrors as output mirrors.

The increase in the width of the reflection spectrum in the case of FBGs did not result in the pulse shortening despite the broadening of the laser emission spectrum. On the contrary, the pulse duration even increased, which is explained, in our opinion, by a stronger influence of the GVD in the FBG on the reflection of radiation with a broader spectrum from it. The pulse duration varied in this case from 50 ps in a laser with a narrowband FBG to 3.5 ns in a laser with a broadband FBG.

By using a Sagnac mirror, we also have failed to reduce the pulse duration despite a considerable increase in the width of the output emission spectrum, which is caused by a stronger influence of the positive GVD in a long fibre resonator in the case of propagation of broadband radiation. Thus, the pulse duration in a laser with the 82 % Sagnac mirror was 170 ps at a wavelength of 1160 nm at the maximum average power of 7.8 mW.

The results obtained in the paper show that short pulses can be obtained by changing the intracavity GVD. However, the use of the known methods (prism and grating compensators, microstructure fibres with the negative GVD) is complicated due to a small gain in the bismuth-doped active fibre.

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